

Modelling of the thermal state and the melting loss of a graphite electrode in the conditions of the evaporative cooling in the arc furnace

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Abstract. The cost of the graphite electrodes amounts greater proportion in the final value of the finished product. This calls for finding opportunities to reduce the maintenance costs of AC and DC furnaces used in foundries. The aim of the study is the creation of a mathematical model and the analysis of the efficiency of the evaporative cooling method in reducing the amount of the graphite electrodes used in small capacity arc furnaces. The mathematical model and the computer program allow determining the thermal state of the electrode and the melting loss of the graphite, the model is developed for a primarily cylindrical electrode and takes into account: the current passing through an electrode, the time of the electrode being in the electrified furnace, and the parameters of the water evaporative cooling. The paper presents the received data about the melting loss of the graphite per ton of steel against the water consumption during the evaporative cooling. The graphite consumption in the arc furnaces of 10–12 tons’ capacity is reduced by 40 %. The recommended water consumption for the evaporative cooling of electrodes for all types of foundry furnaces is 0.1–0.2 m³/h.

1. Introduction

When melting metal in electric arc furnaces, some of the most expensive consumable materials are the graphite electrodes (GE). The expenditures on them amount up to 30 % of the total cost of the finished metal output, while their share in the prime cost of the foundry alloys is higher than the share of the consumed electric energy [1]. Besides, the price policy in the sphere of consumable materials and the finished products is under the influence of the world economic situation [2]. All this requires a search for the ways of reducing maintenance costs on graphite electrodes.

The main factors, determining the rate of consumption of graphite electrodes, are [3, 4]:

- the oxidation of the side and end surfaces (37 %);
- the thermal and mechanical fracture (35 %);
- the oxidation of the end parts (7 %);
- the field emission (10 %);
- the unsafe structures of the electrode clamps and nipples (3 %);
- the bending and impact loads (5 %);
- the graphite fracture caused by the liquid metal bath (3 %).



It is obvious, that one of the factors significantly influencing the amount of used graphite electrodes is their thermal and mechanical fracture and the subsequent oxidation of the side and end surfaces, determined by the electrode temperature and the availability of cooling.

There are various methods and ways of contributing to the prolongation of an electrode life: the strict limits in the use of the technological modes (working should be carried out with regard to the rating power at less current consumption, with an increased demand for making the charging basket and so on); putting a protective coating on the side surface of an electrode. There are several ways of reducing the destructive thermal impact on an electrode. Some of them are the use of a hollow graphite electrode (the inert gas supply through the axial passage results in the electrode cooling and additional arc stabilization), spraying of the coolant (water) under the electrode clamp onto the side surface of graphite electrodes [2, 5–7].

The drawbacks of the methods of putting protective coatings are: the high cost of the applied coating materials, the necessity of the additional technological operations connected with the coating process. Besides, the coating is not durable enough and requires new covering after every casting operation. The paper [8] demonstrates that the consumption of graphite electrodes mainly depends on the uneven thermal load during a casting operation. To reduce the temperature of the graphite electrodes, a forced cooling can be used, such as feeding an inert gas through the central axial passage of an electrode [2, 9]. It should be noted, that as the mathematical modelling points to the ineffective use of gas cooling through the axial passage, which allows removing only an insufficient amount of heat from the electrode, as the gas has a small heat capacity and quickly achieves the temperature comparable with the temperature of the electrode itself [9].

There is a well-known way of reducing the used amount of the electrodes by evaporative cooling. This method is considered to be the most promising and is used in powerful and UHP electric arc furnaces both in Russia and abroad [8–10]. Nowadays, it is mainly applied in large capacity steel making electric furnaces. For instance, in Russia the described system of the evaporative cooling is used in EAF-180, while in Byelorussia it is applied in EAFs-100 [10].

The system of evaporative cooling consists of a spray ring, fixed under the electrode clamp, to spray water onto its side surface (Figure 1). The water control takes place by means of a pressure regulator and valves. Water can be continuously sprayed up or down onto the outer periphery of a graphite electrode at 10–35° angle with regard to the level [11]. The system of electrode's water cooling can be fixed under the coupling band of the electrode clamp [10]. Our observations point out that the spray rings reduce the used amount of electrodes and contribute to the increase of the service life of the electrode clamp and the surrounding isolation [12].

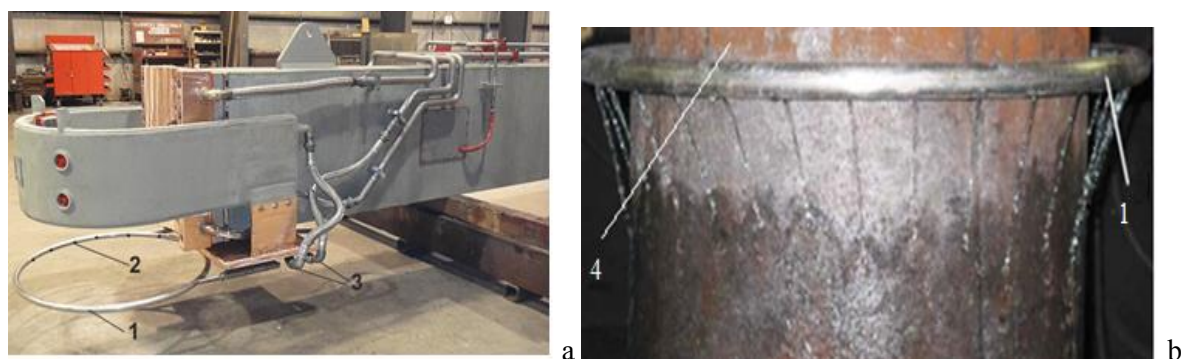


Figure 1. The design of the evaporative cooling system: a – a general view [15]; b – a spray ring around a graphite electrode; 1 – a ring around a graphite electrode; 2 – water spray nozzles for the water supply to an electrode; 3 – tubes for the supply and discharge of water used for the evaporative cooling; 4 – a graphite electrode.

The paper raises the issue of the effectiveness of the application of the forced evaporative cooling in small capacity electric arc furnaces. They are widely used in iron and steel founding and have an

integrated work-cycle, including both the oxidation and the reduction periods. In doing so, there appear some problems connected with the choice of an efficient design, parameters of the evaporative cooling system and the valuation of its economic efficiency. In many ways, the solutions of these problems are determined by the knowledge of the parameters of cooling: the appropriate pressure and water consumption, the speed of water flow down the electrode, the time of switching the water supply on when the electrodes are still cold, etc.

The aim of the study is a mathematical model development aimed at evaluating the efficiency of the evaporative cooling in terms of reducing the amount of used graphite electrodes in small capacity electric arc furnaces (EAF).

2. The mathematical model of the thermal state and the melting loss of a graphite electrode

The mathematical model of the thermal state of an electrode with the diameter $D = 2R$ and the height H includes the heat equation in the cylindrical coordinate system (regarding the axial symmetry and auto thermal heat supply sources) [9]

$$\frac{\partial t}{\partial \tau} = \frac{1}{c \cdot \gamma} \left[\frac{\partial}{\partial r} \left(\lambda \frac{\partial t}{\partial r} \right) + \frac{\lambda}{r} \frac{\partial t}{\partial r} + \frac{\partial}{\partial z} \left(\lambda \frac{\partial t}{\partial z} \right) \right] + \frac{q_v}{c \cdot \gamma} \quad (1)$$

where $0 < r < R$, $0 < z < H$; c, γ is the thermal capacity and the density of the electrode material respectively; $q_v = 16 \cdot I_a^2 \rho / (\pi^2 \cdot D^4)$ is the volume power of auto thermal heat supply sources in a voltage carrying electrode; λ, ρ, c, γ are the heat conduction coefficient, the electric resistivity, the thermal capacity and the density of electrode material respectively; I_a is the arc current (the root-mean-square value for the alternative current).

The boundary problem involves a number of boundary conditions. The preliminary conditions are $t(r, z) = t_0$. Firstly, the evaluation of the heat flux from the arc at the electrode tip is carried out. Because the electric arc is more often at the end of the electrode tip, the heat flux q_a receives a higher value and is determined by the parabolic law, $q_a(r) = \eta_a \bar{q} + 3 \cdot (1 - \eta_a) \bar{q} (r/R)^2$, where $\bar{q} = 4 \cdot I_a U_e / (\pi \cdot D^2)$ – is an average of the heat flux arriving at the electrode tip from the electric arc; U_e – is the near-electrode voltage drop; $\eta_a \approx 0.3$ is the fraction of the heat capacity of the arc, generated in the middle of the electrode tip.

We also set the third class boundary conditions of the heat exchange with the surrounding furnace atmosphere due to the convection q_{conv} and the heat exchange with the working wall surfaces of the furnace caused by the radiation q_{rad} (the water cooling is not applied) as well as the third class boundary conditions of the heat exchange with the cooling water, fed to the side surface of the electrode.

The heat-mass exchange in water moving along the side surface of an electrode is rather complicated, that is why a number of assumptions are taken into account:

- the gas is not saturated, being away from the liquid, at the same time there appears a substance flow, directed away from the surface where the evaporation takes place;
- the heat flux from the electrode surface and the surrounding atmosphere is directed to the liquid;
- the temperature of the water heat is not taken into account until it reaches the saturation point;
- all the heat absorbed by the liquid is spent on its evaporation and releases with the vapour (adiabatic process of evaporation);
- the water flows along the vapour film with the constant speed W_0 ;

The heat-balance equation is written regarding these assumptions,

$$\alpha_s (t_w - t_s) + q_{\text{env}} = \psi J \quad (2)$$

where q_{env} is the heat flux of radiation and convection on the surface of water by the furnace; ψ is the heat of water vaporization; J is the mass of the evaporating water per surface unit; α_s is the surface heat transfer coefficient; t_w is the water temperature; t_s is the temperature of the side surface of the electrode.

The depth of the water film δ changes along the electrode due to the evaporation,

$$\frac{d\delta(y)}{d\tau} = -\frac{J(y)}{\gamma_w} \quad (3)$$

where $J(y)$ is the steam- mass flow along the electrode; γ_w is the water density; τ is the time when the water is in the furnace; $y = H - z$.

To solve the differential equation (3), a boundary condition is added, $\delta|_{y=0} = \delta_0$, where $\delta_0 = Q_w / (\pi D \cdot W_0)$ is the depth of the water film in the area of its feeding with a volumetric water discharge Q_w . Knowing the thermal state of an electrode one can determine the linear velocity of the graphite melting loss,

$$v(T) = \frac{V(T)}{3600 \cdot \gamma_g}, \text{ m/c} \quad (4)$$

where $V(T)$ is the velocity of graphite melting loss due to the temperature, γ_g is the graphite density.

To calculate the thermal melting loss of the graphite electrode, the experimental dependence of the speed of the graphite melting loss (due to the oxidation and thermo-mechanical fracturing) on its temperature in the open air $V(T)$ is used [5, 13]. Regarding the empirical data, an approximation equation is received,

$$V(T) = \xi \cdot 10^{a \lg(T)^2 + b \lg(T) + c}, \text{ kg/(m}^2 \text{ h)} \quad (5)$$

where $a = 4.9627$; $b = -23.836$; $c = 27.167$; T is the temperature, K, $\xi = 0.3 - 1$ is the parameter determining the resistance of the graphite electrode to the thermal loss.

The mass melting loss of graphite from the side surface of the electrode ($r = R$),

$$Q_b = \frac{dm}{d\tau} = \int_F V(T) dF = 2\pi R \int_0^H V(T) dz, \text{ kg/h.}$$

By analogy, the mass melting loss of graphite from the lower tip of an electrode ($z = 0$),

$$Q_t = \frac{dm}{d\tau} = \int_F V(T) dF = 2\pi \int_0^R V(T) r dr, \text{ kg/h.}$$

The total velocity of graphite melting loss Q_Σ and the mass loss Δm at a time τ_k from one graphite

electrode, $Q_\Sigma = Q_b + Q_t$, $\Delta m = \int_0^{\tau_k} V_\Sigma d\tau$.

The energy emitted in the arc of the DC EAFs is determined as $P_o = I_o \cdot U_o$, while the energy in the three arcs of three phase AC EAFs is determined as $P_a = 3 \cdot I_a^* U_a^*$, where $I_a = 16$ kA, the ampere rating of an arc of the DC EAF; I_a^* is the active ampere rating of the arc of three phase AC EAF. An approximate ratio of currents passing through the graphite electrodes of tree phase AC EAF and DC EAF $I_a^* = 1.2 I_a / 3$. Is calculated regarding the same energy of the furnaces under consideration.

A computer program 'Modelling of the thermal state of an electrode of EAF' is developed to provide the calculation under the given mathematical model. It allows determining the thermal state and the graphite melting loss for the preliminary cylindrical electrode in dependence on the current passing through the electrode and the time of its being in the electrified furnace as well as the parameters of the water cooling.

3. The results of computer modelling

The foundry engineering uses arc furnaces with the capacity of 0.5–25 tons. To carry out the computer modelling, the performance specifications of EAF, used for shaped casting with the capacitance from 0.5 to 25 tons are taken from the work [14]. The following performance specifications of electric arc furnaces are used in the presented calculations: $t_0 = 20\text{ }^{\circ}\text{C}$; the near-electrode voltage drop in the arc is 8 V; the emissivity factor of lining is 0.93; its working temperature is $1400\text{ }^{\circ}\text{C}$; the temperature of gases in the furnace is $1200\text{ }^{\circ}\text{C}$; the duration of heat is 1 hour. The thermophysical properties of a graphite electrode are: $c = 2.1\text{ kJ}/(\text{kg}\cdot\text{K})$; $\gamma = 1700\text{ kg}/\text{m}^3$; the emissivity factor of the graphite is 0.71; $\rho = 5\text{ microOhm}\cdot\text{m}$; $\lambda = 120\text{ W}/(\text{m}\cdot^{\circ}\text{C})$. The parameters of the water, cooling an electrode are: the preliminary temperature is $20\text{ }^{\circ}\text{C}$; $\psi = 2.3\text{ MJ}/\text{kg}$; the emissivity factor of the water is 0.5; $\gamma_w = 1000\text{ kg}/\text{m}^3$; $W_0 = 0.3\text{ m/s}$; the evaporative cooling time-on after inserting a cold electrode in a furnace is 60 seconds.

Figure 2 shows the received dependences of the discharge intensity of graphite per ton of steel on the consumption of water, fed for the evaporative cooling in EAFs with the capacitance from 0.5 to 25 tons. It is established that for almost all furnaces there is a significant decrease in the melting loss of graphite electrodes. It is clear that the less the furnace capacitance, the higher the melting loss of graphite electrodes. If the water consumption is over $0.2\text{ m}^3/\text{h}$ the melting loss of electrodes decreases insufficiently.

Figure 3 shows the dependence of the graphite consumption on the furnace capacitance, provided the presence or absence of evaporative cooling with the water consumption of $0.1\text{ m}^3/\text{h}$. The decrease of graphite loss for the furnaces with the capacitance of 0.5–6 tons averages 28 %, for the furnaces with the capacitance of 10–12 tons it amounts to 40 %, for the furnaces of 25 tons it is 11.5 %. It is established that the water supply to the system of evaporative cooling is mostly efficient after current switching in the 3–5 minutes interval.

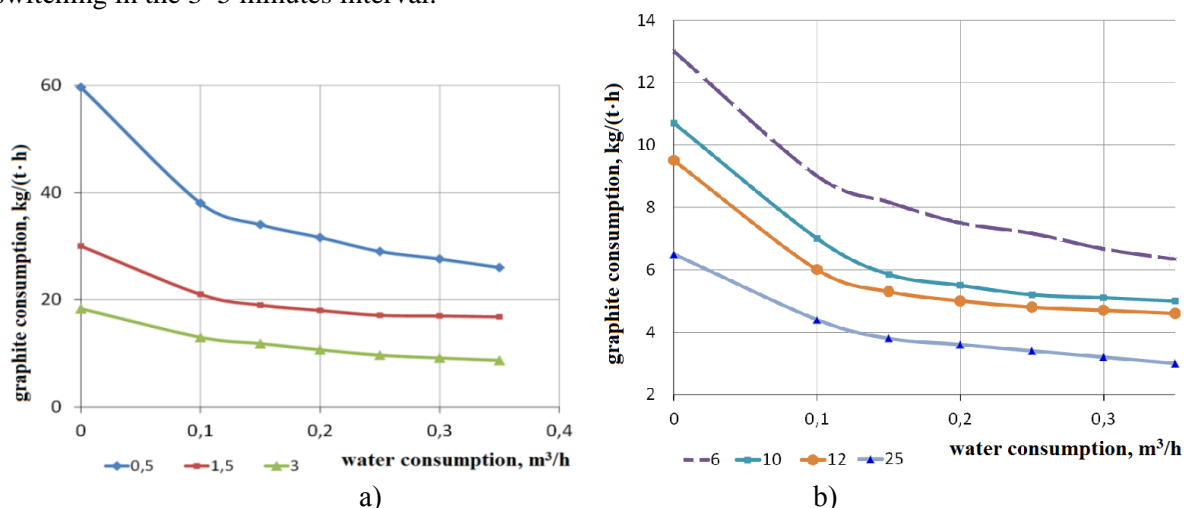


Figure 2. The dependence of the graphite consumption per ton of steel on the consumption of water, fed for evaporative cooling

a – for EAFs with the capacitance from 0.5 to 3 tons; b – for EAFs with the capacitance from 6 to 12 tons.

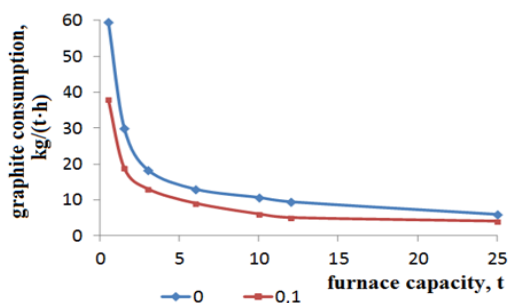


Figure 3. The dependence of the graphite consumption on the furnace capacitance:
 1 – with the use of cooling,
 2 – with the use of evaporative cooling at the water rate of 0.1 m³/h.

4. Conclusion

1. A mathematical model of the thermal state and the melting loss of graphite electrodes has been created for the working at the nominal current of three phase AC EAFs and DC EAFs of small capacitance.

2. It is estimated that the use of the evaporative cooling in arc electric furnaces with the capacity of 0.5–25 tons decreases the temperature of the graphite electrode mostly in its upper area, which results in the less amount of the used graphite electrodes due to the less oxidation of their side surface and the thermo-mechanical fracture.

3. The use of the evaporative cooling of graphite electrodes can be recommended for reducing their consumption both in the existing and planned electric arc furnaces with the capacity of 3–12 tons. The recommended water consumption in cooling electrodes for all types of foundry furnaces should amount to 0.1–0.2 m³/h.

References

- [1] Grudnickij O M, Ishakov R A-R and Korobov V K 2011 *Ways to reduce the specific consumption of graphitized electrodes on electric steelmaking furnaces* (Lit'e i metallurgija) no 1 pp 100–1
- [2] Yachikov I M, Portnova I V and Bystrov M V 2019 *Mathematical and software systems in the industrial and social fields* vol 7 no 1 pp 24–9
- [3] Brusa E 2014 Thermomechanical coupling effect of graphite electrodes upon the electric arc furnace dynamics *Meccanica* vol 49 pp 2979–90
- [4] Yachikov I M, Portnova I V and Bystrov M V 2019 *Materials Science Forum* vol 946 pp 444–9
- [5] Schwabe W E 1971 *The Mechanics of Consumption of Graphite Electrodes in Electric Steel Furnaces* (Electric Furnace Proceedings) pp 140–5
- [6] Dyskina B Sh and Kabanova T V 2014 *Advances in Chemistry and Chemical Technology* vol 10 pp 39–41
- [7] Stopar K, Kovačič M, Kitak P and Pihler J 2017 *Materials and Manufacturing Processes* vol 32 pp 1189–200
- [8] Yachikov I M, Portnova I V and Bystrov M V 2018 *Proceedings of the Fifteenth Congress of Steelmakers* (Yekaterinburg) pp 180–6
- [9] Filippov V V, Matochkin V A, Tishchenko V A and Gulyaev M P 2002 *Casting and metallurgy* no 1 pp 80–3
- [10] Jachikov I M, Portnova I V and Bystrov M V 2018 *Modern scientific achievements of metallurgical heat engineering and their implementation in industry, Sat. doc. II International scientific-practical. conf.* pp 203–8
- [11] Nakamoto Y 1990 Patent 4941149 US.
- [12] Chakrabarti A K 2006 *Steel Making* (PHI Learning Pvt. Ltd)
- [13] Okorokov N V 1971 *Arc Furnaces* (Moscow)
- [14] Bogdanov S P 2006 *Calculation of arc steel-smelting furnaces* (St. Petersburg)